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High resolution ^{148}Nd(^{3}He,nγ) two proton stripping reaction and the structure of the 0_2^+ state in ^{150}Sm

J. F. Sharpey-Schafer[1,a], P. Papka[2,3], S. P. Bvumbi[4], P. M Jones[3], P. Vymers[2], T. D. Bucher[3], T. S. Dinoko[1], J. L. Easton[1,3], M. S. Herbert[1], B. V. Kheswa[2,3], N. Khumalo[5], E. A. Lawrie[3], J. J. Lawrie[3], S. N. T. Majola[3,6], J. Ndayishimye[2,3], D. Negi[3], S. P. Noncolela[1,3], J. N. Orce[1], O. Shirinda[3], P. Sithole[1,3], M. A. Stankiewicz[3,6] and M. Wiedeking[3]

[1]University of Western Cape, Department of Physics, P/B X17, Bellville 7535, South Africa
[2]Stellenbosch University, Department of Physics, P/B X1, Matieland 7602, South Africa
[3]iThemba LABS, National Research Foundation, PO Box 722, Somerset-West 7129, South Africa
[4]University of Johannesburg, Department of Physics, PO Box 524, Auckland Park 2006, South Africa
[5]University of Zululand, Department of Physics, P/B X1001, Kwa Dlangezwa 3886, South Africa
[6]University of Cape Town, Department of Physics, P/B X3, Rondebosch 7701, South Africa
[a] Corresponding author: jfss@tlabs.ac.za

Abstract. The challenge of achieving high resolution in binary reactions involving an outgoing high energy neutron is solved by detecting the γ-ray decay of populated excited states in an array of escape suppressed HPGe detectors in coincidence with fast neutrons detected in a wall of scintillator detectors 2m down beam of the target. The selectivity of the arrangement is of the order of 1 in 1000. The time-of-flight difference is sufficient to separate fast neutrons from direct reactions from a large background of statistical neutrons from fusion-evaporation reactions. Our interest is in the wavefunction of the 0_2^+ state at 740 keV in the N=88 nucleus ^{150}Sm which, with the 0_2^+ state in ^{100}Ru, are the only two excited states observed in 2β2ν double β-decay.

The 0_2^+ state at 740 keV in the N=88 nucleus ^{150}Sm is one of only two excited states observed [1] in 2β2ν double β-decay. The other state is the 1130 keV 0_2^+ state in ^{100}Mo. The importance of understanding the microscopic configurations of these 0_2^+ states, and of the ground 0_1^+ states of the parent and daughter nuclei, has been stressed in a recent review article [2]. The better the transition matrix elements can be calculated, the more accurately an effective neutrino mass can be extracted. There is also the ambition of using the double γ-ray decay from the 0_2^+ states to give a four-fold coincidence with the two electrons to improve the sensitivity of experiments so that the level of $\approx 10^{24}$ y partial half-life can be achieved. This is the estimated sensitivity required to detect 2β0ν neutrinoless double decay to determine the Majorana/Dirac nature of neutrinos.

The N=88 nuclei have remarkable features; they are at a peak in the $|M(E3)|^2$ strength of $0_1^+ \rightarrow 3_1^-$ transitions for even-even nuclei as a function of neutron number [3]; they also have very strong E0 transitions from the band built on the 0_2^+ states to the ground state bands [4,5]. It has been established [6,7] that the 0_2^+ states in N=88 and 90 nuclei are not β-vibrations [8] but 2p-2h neutron states lowered into the pairing gap by configuration dependent pairing. They are classic examples of 'pairing isomers' forming a 'second vacuum' [6] on which a complete set of excited deformed states are built that are congruent to those built on the 0_1^+ ground state. We have made extensive spectroscopic measurements in the nucleus ^{150}Sm [9] reporting on the first observation of consistent E1 transitions in deformed nuclei from the levels in the first excited 0_2^+ band to the lowest negative parity band (Fig. 1). Our contention is that these 0_2^+ states have a predominantly paired, seniority zero, neutron configuration. We wished to establish the paired proton content of this state in ^{150}Sm by populating it in a high resolution two proton stripping (^{3}He,n) direct reaction.

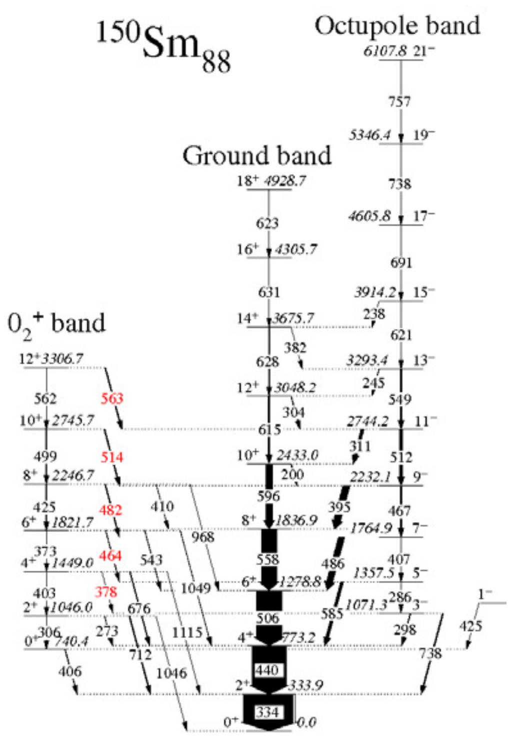

Figure 1. Partial decay scheme of ^{150}Sm from [9].

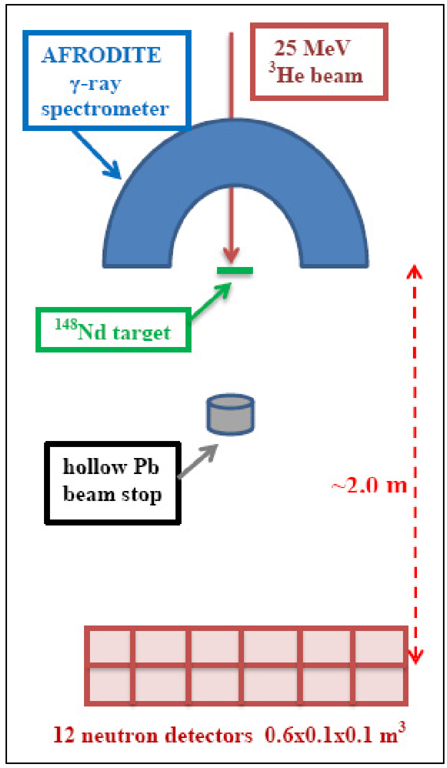

Figure 2. Schematic diagram of the apparatus.

A schematic diagram of the experimental set-up is shown in Fig. 2. We used 25 MeV beams of ^{3}He ions from the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) separated sector cyclotron (SSC) to bombard a 5.2 mg cm^{-2} target of ^{148}Nd. Neutrons were detected in a double wall of twelve 0.6x0.1x0.1 m^3 NE102A plastic scintillators subtending scattering angles to the target between 0º and 10º. These scintillators have no n-γ discrimination so some shielding may be used to reduce the γ-ray flash from the target. Otherwise the residual γ-rays were separated from the neutrons by time-of-flight (T-o-F) over the 2.0 m flight path from the target to the scintillation neutron detectors. The ^{148}Nd(^{3}He,n)^{150}Sm direct reaction has a Q-value of +6.512 MeV so that these direct reaction neutrons had an energy of about 30 MeV, a velocity of 69 mm/ns (v/c = 23%) taking ~30 ns to travel 2.0 m. The main fusion evaporation channels are (^{3}He,3n)^{148}Sm and (^{3}He,4n)^{147}Sm, in the ratio 2:1, and are at least 10^3 stronger than the (^{3}He,n)^{150}Sm channel. Evaporation neutron yields peak below 2 MeV and took ~130 ns to travel a distance of 2.0 m. The statistical neutrons are emitted isotropically, whereas the *L=0* neutrons from (^{3}He,n) direct reactions have most of their cross-section peaked within θ_{lab} = 10° of 0° [10]. The γ-rays from excited states were detected in the iThemba LABS escape suppressed γ-ray spectrometer array AFRODITE [11] consisting of 9 HPGe clover detectors in bismuth germanate (BGO) shields.

The γ-rays that we observe in coincidence with fast neutrons are shown in Fig. 3. A background has been subtracted of γ-rays in coincidence with slower neutrons. The spectrum contains only a few γ-rays belonging to the ground-state band in ^{150}Sm and the 0_2^+ state which is only very weakly populated. We are surprised to see the yrast states so clearly. The neutron detectors are strongly selecting *L=0* states and the only way the yrast 2^+, 4^+ and 6^+ states should be populated is by *L = 2, 4* and *6* transitions respectively. The experimental data suggest that the incoming ^{3}He must Coulomb or inelastically excite the target nucleus to the yrast 2^+, 4^+ and 6^+ states in ^{148}Nd and then subsequently have *L=0* two proton transfer to the yrast 2^+, 4^+ and 6^+ states in ^{150}Sm. Inelastic excitations in direct reactions have been studied extensively by Ascuitto and colleagues [12-14] but have otherwise been largely ignored.

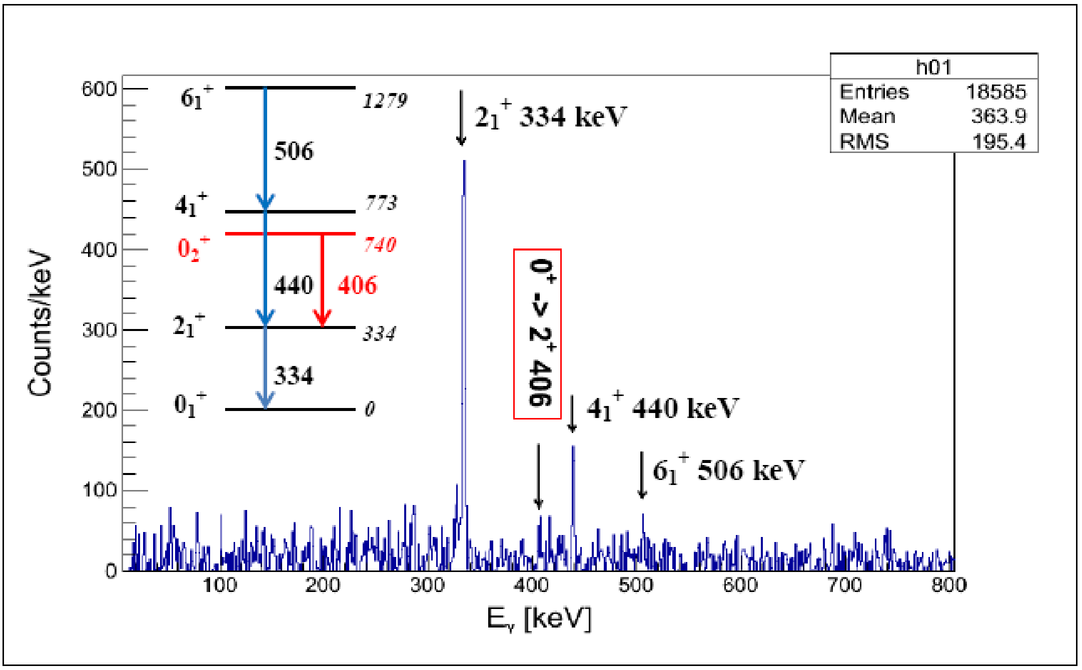

Figure 3. A spectrum of γ-rays from ^{150}Sm in coincidence with direct reaction fast neutrons from ^{148}Nd(^{3}He,n)^{150}Sm at E_{lab} = 25 MeV. A background spectrum in coincidence with slower neutrons has been subtracted.

A problem with our experimental technique is that we do not detect the two proton stripping to the ground state as it does not decay by γ-rays. However, a way of estimating the absolute yields is to fit our relative yields of excited states to the line shapes of the low resolution T-o-F data in Ref. [10]. In Fig. 4 we show such a fit to the ground state transition seen in the ^{148}Nd(^{3}He,n)^{150}Sm reaction at E_{lab} = 25.4 MeV and zero degrees using a 9 m flight path and a time resolution of 1 ns ≈ 450 keV (figure 1 of Ref. [10]). The transitions to the ground 0_1^+ state and the first excited 2_1^+ state at 334 keV are barely resolved in the data of [10]. In the fit we have combined the intensities of the transitions from the 0_2^+ and 4_1^+ states decaying by γ-rays with energies of 406 and 440 keV respectively. In Table 1 we compare the relative intensities of the transition strengths to the lowest states in ^{150}Sm where we have normalised them to 100 for the 2_1^+ state. The data for the 4_1^+ state is in reasonable agreement for both the γ-ray data and the T-o-F data, considering the resolution of the latter and the difficulties in fitting such data. We conclude that the population of the 0_2^+ state is less than about 5% of the transition strength to the ground state. This supports the view that the 0_2^+ state is a neutron pairing isomer and nothing to do with the mixing of coexisting shapes [15].

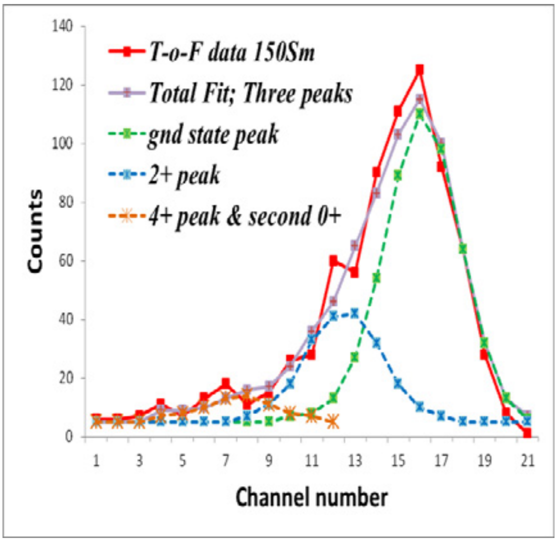

Figure 4. Fits to the Time-of-Flight ^{148}Nd(^{3}He,n)^{150}Sm data of Ref. [10]. See text for details.

Table 1. Comparison between the gamma-ray intensities observed in our experiment and the intensities deduced for the corresponding transitions from the fit to the data of Ref. [10] shown in Fig. 4.

Level	E_γ (keV)	γ-ray data	Fit to T-o-F
0_1^+	0	--	271(19)
2_1^+	334	100(5)	100
4_1^+&0_2^+	440	34(4)	22(6)
6_1^+	506	13(2)	--

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